8 Energy

Chapter 8 develops the concept of energy. Emphasis is on mechanical energy, potential and kinetic, with acknowledgment of other forms and applications. The key concept is the conservation of energy.

The mechanical energy of the wind can be harnessed to produce electrical power.

Energy is the most central concept underlying all of science. Surprisingly, the idea of energy was unknown to Isaac Newton, and its existence was still being debated in the 1850s. Even though the concept of energy is relatively new, today we find it ingrained not only in all branches of science, but in nearly every aspect of human society. We are all quite familiar with energy. Energy comes to us from the sun in the form of sunlight, it is in the food we eat, and it sustains life. Energy may be the most familiar concept in science, yet it is one of the most difficult to define. Persons, places, and things have energy, but we observe only the effects of energy when something is happening—only when energy is being transferred from one place to another or transformed from one form to another. We begin our study of energy by observing a related concept, work.

Videotape: Show "Energy" from the series *Conceptual Physics Alive!*

8.1 Work

Important Terms

joule
work

When discussing whether or not work is done, be sure to specify *done on what.* If you push a stationary wall, you may be doing work on your muscles that involves forces and distances in flexing. However, you do no work on the wall. Key point: If work is done on something, then the energy of that something changes.

The previous chapter showed that the change in an object's motion is related to both force and how long the force acts. "How long" meant time. Remember, the quantity *force* × *time* is called *impulse.* But "how long" need not always mean time. It can mean distance also. When we consider the quantity *force* × *distance,* we are talking about an entirely different concept. This concept is called **work.**

We do work when we lift a load against the earth's gravity. The heavier the load or the higher we lift it, the more work we do. Two things enter into every case where work is done: (1) the *application of a force,* and (2) the *movement of something* by that force.

Let's look at the simplest case, in which the force is constant and the motion takes place in a straight line in the direction of the force.

igure 8.1 ▲
Vork is done in lifting the bar-ell. If the barbell could be lifted wice as high, the weight lifter vould have to do twice as much vork.

Vith each contraction of the veight lifter's heart, a force is xerted through a distance on is blood and so does work on ne blood. But this work is not one on the barbell.

joule is the work done in ver-cally lifting a quarter-pound amburger with cheese approx. 1 N) one meter.

Then the work done on an object by an applied force is the product of the force and the distance through which the object is moved.*

$$\text{work} = \text{force} \times \text{distance}$$

In equation form,

$$W = Fd$$

If we lift two loads up one story, we do twice as much work as we would in lifting one load the same distance, because the *force* needed to lift twice the weight is twice as great. Similarly, if we lift one load two stories instead of one story, we do twice as much work because the *distance* is twice as great.

Notice that the definition of work involves both a force *and* a distance. A weight lifter holding a barbell weighing 1000 N over his head does no work on the barbell. He may get really tired holding it, but if the barbell is not moved by the force he exerts, he does no work on the barbell. Work may be done on the muscles by stretching and squeezing them, which is force times distance on a biological scale, but this work is not done on the barbell. Lifting the barbell, however, is a different story. When the weight lifter raises the barbell from the floor, he is doing work on it.

Work generally falls into two categories. One of these is the work done against another force. When an archer stretches her bowstring, she is doing work against the elastic forces of the bow. Similarly, when the ram of a pile driver is raised, work is required to raise the ram against the force of gravity. When you do push-ups, you do work against your own weight. You do work on something when you force it to move against the influence of an opposing force—often friction.

The other category of work is work done to change the speed of an object. This kind of work is done in bringing an automobile up to speed or in slowing it down.

The unit of measurement for work combines a unit of force, N, with a unit of distance, m. The resulting unit of work is the newton-meter (N·m), also called the **joule** (rhymes with cool) in honor of James Joule. One joule (J) of work is done when a force of 1 N is exerted over a distance of 1 m, as in lifting an apple over your head. For larger values we speak of kilojoules (kJ)—thousands of joules—or megajoules (MJ)—millions of joules. The weight lifter in Figure 8.1 does work on the order of kilojoules. To stop a loaded truck going at 100 km/h takes megajoules of work.

8.2 Power

mportant Terms

power
vatt

The definition of work says nothing about how long it takes to do the work. When carrying a load up some stairs, you do the same amount of work whether you walk or run up the stairs. So why are you more

* For the more general case, work is the product of the *component* of force acting in the direction of motion and the distance moved.

tired after running upstairs in a few seconds than after walking upstairs in a few minutes? To understand this difference, we need to talk about how fast the work is done, or **power.** Power is the rate at which work is done. It equals the amount of work done divided by the time interval during which the work is done.

$$\text{power} = \frac{\text{work done}}{\text{time interval}}$$

A high-power engine does work rapidly. An automobile engine that delivers twice the power of another automobile engine does not necessarily produce twice as much work or go twice as fast as the less powerful engine. Twice the power means the engine can do twice the work in the same amount of time or the same amount of work in half the time. A powerful engine can get an automobile up to a given speed in less time than a less powerful engine can.

The unit of power is the joule per second, also known as the **watt,** in honor of James Watt, the eighteenth-century developer of the steam engine. One watt (W) of power is expended when one joule of work is done in one second. One kilowatt (kW) equals 1000 watts. One megawatt (MW) equals one million watts. In the United States, we customarily rate engines in units of horsepower and electricity in kilowatts, but either may be used. In the metric system of units, automobiles are rated in kilowatts. One horsepower, hp, is the same as 0.75 kW, so an engine rated at 134 hp is a 100-kW engine.

Figure 8.2 ▲
The three main engines of the space shuttle can develop 33 000 MW of power when fuel is burned at the enormous rate of 3400 kg/s. This is like emptying an average-size swimming pool in 20 seconds!

A watt of power is the work done in vertically lifting a quarter-pound hamburger with cheese (approx. 1 N) one meter in one second.

You can tell students that to lift a quarter-pound hamburger with cheese 1 m in 1 s requires one watt of power.

Question

If a forklift is replaced with a new forklift that has twice the power, how much greater a load can it lift in the same amount of time? If it lifts the same load, how much faster can it operate?

8.3 Mechanical Energy

Important Terms

energy
mechanical energy

Mechanical energy underlies many of the other forms of energy.

When work is done by an archer in drawing a bowstring, the bent bow acquires the ability to do work on the arrow. When work is done to raise the heavy ram of a pile driver, the ram acquires the ability to do work on the object it hits when it falls. When work is done to wind a spring mechanism, the spring acquires the ability to do work on various gears to run a clock, ring a bell, or sound an alarm.

In each case, something has been acquired that enables the object to do work. It may be in the form of a compression of atoms in the material of an object; a physical separation of attracting bodies; or a rearrangement of electric charges in the molecules of a substance.

Answer

The forklift that delivers twice the power will lift twice the load in the same time, or the same load in half the time. Either way, the owner of the new forklift is happy.

DOING PHYSICS

Doing Work on Sand

Pour a handful of dry sand in a can with a cover. Measure the temperature of the sand with a thermometer. Remove the thermometer and cover the can. Shake the can vigorously for a minute or so. You're doing work on the sand as you change its energy—kinetic, potential, or both—depending on how you shake it. After shaking, measure the temperature of the sand again. What happened to the temperature? How can you explain the change?

Activity

This "something" that enables an object to do work is **energy**.* Like work, energy is measured in joules. It appears in many forms that will be discussed in the following chapters. For now we will focus on the two most common forms of **mechanical energy**—the energy due to the position of something, or the movement of something. Mechanical energy can be in the form of either potential energy or kinetic energy.

mportant Term

potential energy

8.4 Potential Energy

An object may store energy by virtue of its position. The energy that is stored and held in readiness is called **potential energy** (PE) because in the stored state it has the potential for doing work. A stretched or compressed spring, for example, has a potential for doing work. When a bow is drawn, energy is stored in the bow. The bow can do work on the arrow. A stretched rubber band has potential energy because of its position. If the rubber band is part of a slingshot, it is also capable of doing work.

The chemical energy in fuels is also potential energy. It is actually energy of position at the submicroscopic level. This energy is available when the positions of electric charges within and between molecules are altered, that is, when a chemical change takes place. Any substance that can do work through chemical action possesses potential energy. Potential energy is found in fossil fuels, electric batteries, and the food we eat.

9

* Strictly speaking, that which enables an object to do work is called its *available energy*, because not all the energy of an object can be transformed into work.

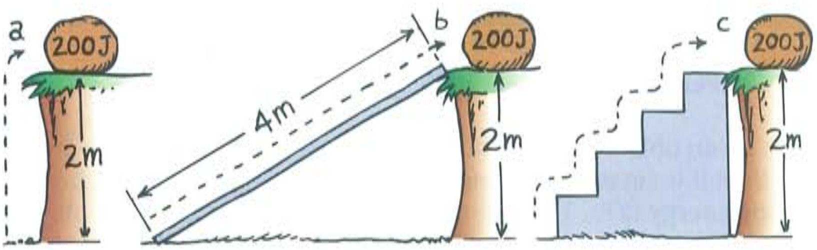


Figure 8.3
The potential energy of the 100-N boulder with respect to the ground below is 200 J in each case because the work done in elevating it 2 m is the same whether the boulder is (a) lifted with 100 N of force, (b) pushed up the 4-m incline with 50 N of force, or (c) lifted with 100 N of force up each 0.5-m stair. No work is done in moving it horizontally, neglecting friction.

Work is required to elevate objects against the earth's gravity. The potential energy due to elevated positions is called *gravitational potential energy.* Water in an elevated reservoir and the raised ram of a pile driver have gravitational potential energy.

The amount of gravitational potential energy possessed by an elevated object is equal to the work done against gravity in lifting it. The work done equals the force required to move it upward times the vertical distance it is moved (remember $W = Fd$). The upward force required while moving at constant velocity is equal to the weight, mg, of the object, so the work done in lifting it through a height h is the product mgh.

$$\text{gravitational potential energy} = \text{weight} \times \text{height}$$

$$\text{PE} = mgh$$

Note that the height is the distance above some chosen reference level, such as the ground or the floor of a building. The gravitational potential energy, mgh, is relative to that level and depends only on mg and h. We can see in Figure 8.3 that the potential energy of the boulder at the top of the ledge does not depend on the path taken to get it there.

You can give the example of dropping a bowling ball on your toe—first from a distance of 1 mm above your toe, then to various distances up to 1 m above your toe. Each time, the bowling ball would do more work on your toe, because it would possess more gravitational potential energy when released.

Questions

1. How much work is done on a 100-N boulder that you carry horizontally across a 10-m room? How much PE does the boulder gain?
2. a. How much work is done on a 100-N boulder when you lift it 1 m?
   b. What power is expended if you lift the boulder a distance of 1 m in a time of 1 s?
   c. What is the gravitational potential energy of the boulder in the lifted position?

Answers

1. You do no work on the boulder moved horizontally, because you apply no force (except for the tiny bit to start and stop it) in its direction of motion. It has no more PE across the room than it had initially.
2. a. You do 100 J of work when you lift it 1 m, since $Fd = 100\ \text{N·m} = 100\ \text{J}$
   b. Power $= \frac{100\ \text{J}}{1\ \text{s}} = 100\ \text{W}$
   c. It depends. Relative to its starting position, the boulder's PE is 100 J. Relative to some other reference level, its PE would be some other value.

10

Figure 8.4 ▲
he potential energy of the rawn bow equals the work average force × distance) done y drawing the arrow into posi-ion. When released, potential nergy will become the kinetic nergy of the arrow.

mportant Term

inetic energy

o a close approximation, skid-ding force is independent of peed. Hence change in KE is pproximately equal to change n skidding distance.

When the car's brakes are pplied, the car's kinetic energy s changed into internal energy n the brake pads, tire, and oad as they become warmer.

8.5 Kinetic Energy

Push on an object and you can set it in motion. If an object is moving, then it is capable of doing work. It has energy of motion, or **kinetic energy** (KE). The kinetic energy of an object depends on the mass of the object as well as its speed. It is equal to half the mass multiplied by the square of the speed.

$$\text{kinetic energy} = \frac{1}{2}\,\text{mass} \times \text{speed}^2$$

$$\text{KE} = \frac{1}{2}mv^2$$

When you throw a ball, you do work on it to give it speed as it leaves your hand. The moving ball can then hit something and push it, doing work on what it hits. The kinetic energy of a moving object is equal to the work required to bring it to that speed from rest, or the work the object can do while being brought to rest.

$$\text{net force} \times \text{distance} = \text{kinetic energy}$$

or in equation notation,*

$$Fd = \frac{1}{2}mv^2$$

Note that the speed is squared, so if the speed of an object is doubled, its kinetic energy is quadrupled ($2^2 = 4$). Consequently, it takes four times the work to double the speed. Also, an object moving twice as fast takes four times as much work to stop. Accident investigators are aware that a car going 100 km/h has four times the kinetic energy it would have at 50 km/h. So a car going 100 km/h will skid four times as far when its brakes are locked than it would at 50 km/h, because speed is squared for kinetic energy.

Figure 8.5 ▶
ypical stopping distance for ars traveling at various speeds. he work done to stop the car is riction force × distance of slide. Notice how work depends on the quare of the speed. The dis-ances would be even greater if he driver's reaction time were aken into account.

Kinetic energy exists in various other forms of energy, such as thermal energy (random molecular motion), acoustical energy (molecules vibrating in rhythmic patterns), and radiant energy (originating from the motions of electrons within atoms). There is much in common among the various forms of energy.

* This formula is derived algebraically as follows. Multiply both sides of $F = ma$, which is Newton's second law, by d to get $Fd = mad$. Recall that for motion in a straight line at constant acceleration, $d = \frac{1}{2}at^2$. So $Fd = ma(\frac{1}{2}at^2) = \frac{1}{2}maat^2 = \frac{1}{2}m(at)^2$. Substituting $v = at$, we get $Fd = \frac{1}{2}mv^2$.

Physics of Sports

The Sweet Spot

The sweet spot of a tennis racquet or a baseball bat is the place where the ball's impact produces minimum vibrations in the racquet or bat. Strike a ball at the sweet spot and it goes faster and farther. Strike a ball in another part of the racquet or bat, and vibrations can occur that sting your hand! From an energy point of view, there is energy in the vibrations of the racquet or bat. There is energy in the ball after being struck. Energy that is not in vibrations is energy available to the ball. Do you see why a ball will go faster and farther when struck at the sweet spot?

Question

When the brakes of a motorcycle traveling at 60 km/h become locked, how much farther will the motorcycle skid than if it were traveling at 20 km/h?

The Best From Conceptual Physics Alive!

Conservation of Energy: Numerical Example

Side 1
Chapter 36

Important Term

law of energy conservation

When gasoline combines with oxygen in a car's engine, the chemical potential energy stored in the fuel is converted mainly into molecular KE (thermal energy). Some of this energy in effect is transferred to the piston and some of this causes motion of the car.

Interactive Physics™ Simulations: 17 Engine Lift, 18 Pendulum I, 19 Pendulum II

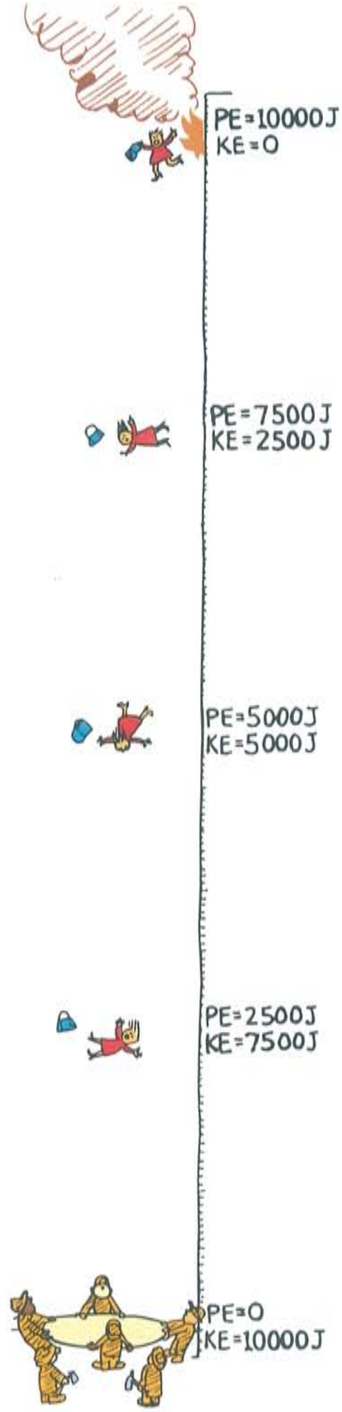
8.6 Conservation of Energy

More important than knowing *what energy is,* is understanding how it behaves—*how it transforms.* We can better understand nearly every process or change that occurs in nature if we analyze it in terms of a transformation of energy from one form to another.

As you draw back the stone in a slingshot, you do work stretching the rubber band. The rubber band then has potential energy. When released, the stone has kinetic energy equal to this potential energy. It delivers this energy to its target, perhaps a wooden fence post. The slight distance the post is moved multiplied by the average force of impact doesn't quite match the kinetic energy of the stone. The energy score doesn't balance. But if you investigate further, you'll find that both the stone and fence post are a bit warmer. By how much? By the energy difference. Energy changes from one form to another. It transforms without net loss or net gain.

Answer

Nine times farther; the motorcycle has nine times as much energy when it travels three times as fast. KE $= \frac{1}{2}m(3v)^2 = \frac{1}{2}m9v^2 = 9(\frac{1}{2}mv^2)$. Ordinarily, the friction force will be the same in either case. Therefore, to do nine times the work requires nine times more sliding distance.



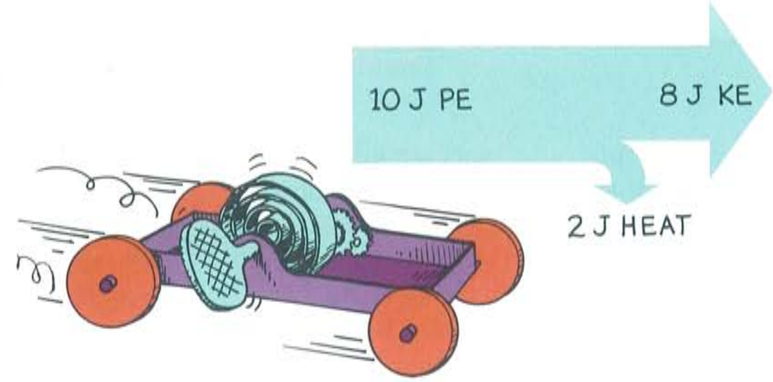


Figure 8.6 ▲
Part of the PE of the wound spring changes into KE. The remaining PE turns into heating the machinery and the surroundings due to friction. No energy is lost.

The study of the various forms of energy and the transformations from one form into another led to one of the greatest generalizations in physics—the **law of conservation of energy:**

> Energy cannot be created or destroyed. It can be transformed from one form into another, but the total amount of energy never changes.

When you consider any system in its entirety, whether it is as simple as a swinging pendulum or as complex as an exploding galaxy, there is one quantity that does not change: energy. It may change form or it may be transferred from one place to another, but the total energy score stays the same.

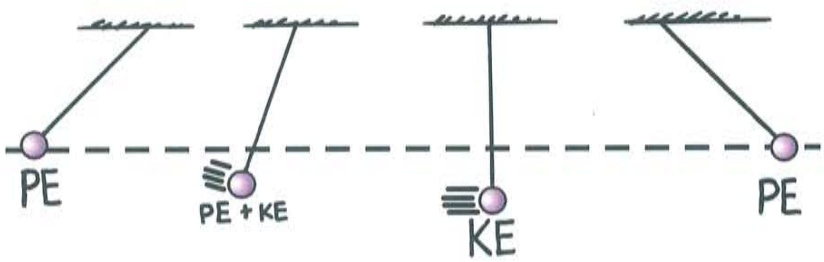


Figure 8.8 ▲
Energy transformations in a pendulum: The PE of the pendulum bob at its highest point is equal to the KE of the bob at its lowest point. Everywhere along its path, the sum of PE and KE is the same. Because of the work done against friction, this energy will eventually be transformed into heat.

Figure 8.7 ▲
When the lady in distress leaps from the burning building, note that the sum of her PE and KE remains constant at each successive position—$\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, and all the way down to the ground.

This energy score takes into account the fact that each atom that makes up matter is a concentrated bundle of energy. When the nuclei (cores) of atoms rearrange themselves, enormous amounts of energy can be released. The sun shines because some of its nuclear energy is transformed into radiant energy. In nuclear reactors, nuclear energy is transformed into heat.

Enormous compression due to gravity in the deep hot interior of the sun causes hydrogen nuclei to fuse and become helium nuclei. This high-temperature welding of atomic nuclei is called *thermonuclear fusion* and will be covered later, in Chapter 40. This process releases radiant energy, some of which reaches the earth. Part of this energy falls on plants, and some of the plants later become coal. Another part supports life in the food chain that begins with microscopic marine animals and plants, and later gets stored in oil. Part of the sun's energy is used to evaporate water from the ocean. Some water returns to the earth as rain that is trapped behind a dam. By virtue of its elevated position, the water behind the dam has potential energy that is used to power a generating plant below the dam. The generating plant transforms the energy of falling water into electric energy. Electric energy travels through wires to homes where it is used for lighting, heating, cooking, and operating electric toothbrushes. How nice that energy is transformed from one form to another!

LINK TO CHEMISTRY

Reactions

What process provides energy for rockets that lift the space shuttle into orbit? What process releases energy from the food we eat? The answer is *chemical reactions.* During a chemical reaction the bonds between atoms *break* and then reform. Breaking bonds requires energy, and forming bonds releases it. Pulling atoms apart is like pulling apart two magnets stuck together; it takes energy to do it. And when atoms join, it is like two separated magnets that slam together; energy is released. Rapid energy release can produce flames. Slow energy release occurs during the digestion of food. The conservation of energy rules chemical reactions. The amount of energy required to break a chemical bond is the same amount released when that bond is formed.

Question

Suppose a car with a miracle engine is able to convert into work 100% of the energy released when gasoline burns (40 million joules per liter). If the air drag and overall frictional forces on the car traveling at highway speed is 500 N, what is the upper limit in distance per liter of gasoline the car could cover at highway speed?

8.7 Machines

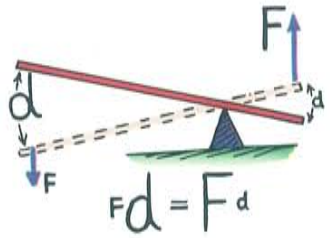
A **machine** is a device used to multiply forces or simply to change the direction of forces. The concept that underlies every machine is the conservation of energy. Consider one of the simplest machines, the lever, shown in Figure 8.9. At the same time we do work on one end of the **lever,** the other end does work on the load. We see that the direction of force is changed. If we push *down,* the load is lifted *up.* If the heat from friction is small enough to neglect, the work input will be equal to the work output.

Answer

Work is defined as force × distance. By rearranging the formula, we get distance = work ÷ force. If all 40 million joules of energy in one liter of gas were used to do the work of overcoming the air drag and frictional forces, the distance would be

$$\text{distance} = \frac{\text{work}}{\text{force}} = \frac{40\ 000\ 000\ \text{J}}{500\ \text{N}} = 80\ 000\ \text{m} = 80\ \text{km}$$

The important point here is that even with a perfect engine, fuel economy has an upper limit that is dictated by the conservation of energy.



igure 8.9 ▲
he lever. The work (force × dis-ance) done at one end is equal o the work done on the load at he other end.

mportant Terms

ulcrum
ever
achine
echanical advantage
ulley

$$\text{work input} = \text{work output}$$

Since work equals force times distance, we can say

$$(\text{force} \times \text{distance})_{\text{input}} = (\text{force} \times \text{distance})_{\text{output}}$$

A little thought will show that the pivot point, or **fulcrum**, of the lever can be relatively close to the load. Then a small input force exerted through a large distance will produce a large output force over a correspondingly short distance. In this way, a lever can multiply forces. However, no machine can multiply work or energy. That's a conservation of energy no-no!

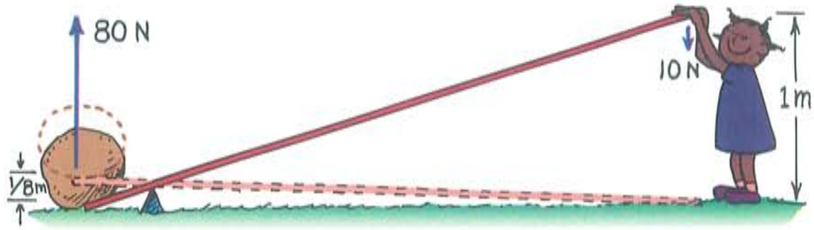
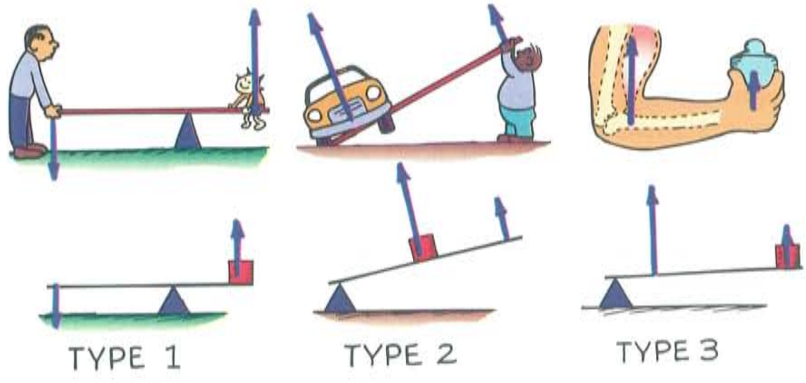


Figure 8.10 ▲
The output force (80 N) is eight times the input force (10 N), while the output distance (1/8 m) is one-eighth of the input distance (1 m).

Consider the ideal weightless lever in Figure 8.10. The child pushes down 10 N and lifts an 80-N load. The ratio of output force to input force for a machine is called the **mechanical advantage**. Here the mechanical advantage is (80 N)/(10 N), or 8. Notice that the load moves only one-eighth of the distance the input force moves. Neglecting friction, the mechanical advantage can also be determined by the ratio of input distance to output distance.

igure 8.11 ▶
he three basic types of levers. otice that the direction of the orce is changed in type 1.



Three common ways to set up a lever are shown in Figure 8.11. A type 1 lever has the fulcrum between the force and the load, or between input and output. This kind of lever is commonly seen in a playground seesaw with children sitting on each end of it. Push down on one end and you lift a load at the other. You can increase force at the expense of distance. Note that the directions of input and output are opposite.

For a type 2 lever, the load is between the fulcrum and the input force. To lift a load, you *lift* the end of the lever. One example is placing one end of a long steel bar under an automobile frame and lifting on the free end to raise the automobile. Again, force on the load is increased at the expense of distance. Since the input and output forces are on the same side of the fulcrum, the forces have the same direction.

In the type 3 lever, the fulcrum is at one end and the load is at the other. The input force is applied between them. Your biceps muscles are connected to the bones in your forearm in this way. The fulcrum is your elbow and the load is in your hand. The type 3 lever increases distance at the expense of force. When you move your biceps muscles a short distance, your hand moves a much greater distance. Notice that the input and output forces are on the same side of the fulcrum and therefore they have the same direction.

A **pulley** is basically a kind of lever that can be used to change the direction of a force. Properly used, a pulley or system of pulleys can multiply forces.

Other examples of levers are
Type 1: crowbar opening a window,
Type 2: a hand bottle cap opener,
Type 3: a construction crane.

Some of your students may have seen a chain hoist being used to remove an automobile engine from a car. The mechanic must pull meters of chain to lift the engine a few centimeters.

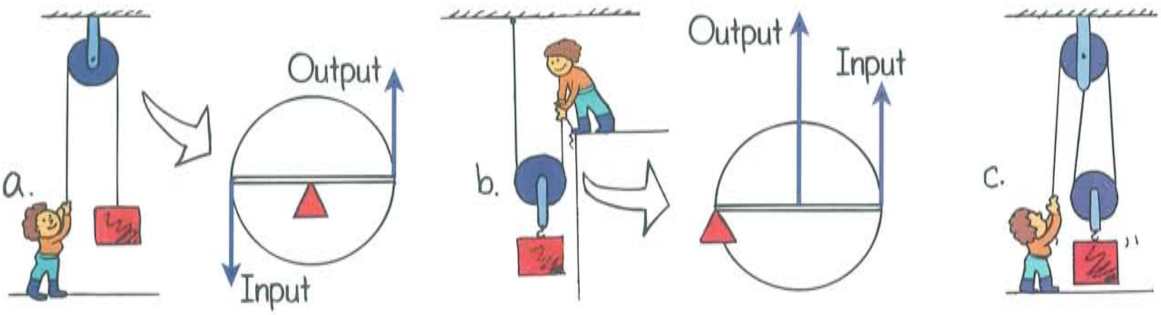


Figure 8.12 ▲
A pulley can (a) change the direction of a force as input is exerted downward and load moves upward, (b) multiply force as input is now half the load, and (c) when combined with another pulley, both change the direction and multiply force.

The single pulley in Figure 8.12a behaves like a type 1 lever. The axis of the pulley acts as the fulcrum, and both lever distances (the radius of the pulley) are equal so the pulley does not multiply force. It simply changes the direction of the applied force. In this case, the mechanical advantage equals 1. Notice that the input distance equals the output distance the load moves.

In Figure 8.12b, the single pulley acts as a type 2 lever. Careful thought will show that the fulcrum is at the left end of the "lever" where the supporting rope makes contact with the pulley. The load is suspended halfway between the fulcrum and the input end of the lever, which is on the right end of the "lever." Each newton of input will support two newtons of load, so the mechanical advantage is 2. This number checks with the distances moved. To raise the load 1 m, the woman will have to pull the rope up 2 m. We can say the mechanical advantage is 2 for another reason: the load is now supported by two strands of rope. This means each strand supports half the load. The force the woman applies to support the load is therefore only half of the weight of the load.

The mechanical advantage for simple pulley systems is the same as the number of strands of rope that actually support the load. In Figure 8.12a the load is supported by one strand and the mechanical advantage is 1. In Figure 8.12b the load is supported by two strands

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Machines: Pulleys

Side 1
Chapter 37

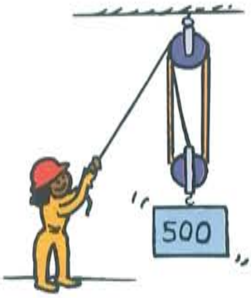


Figure 8.13 ▲
n an idealized pulley system, applied force × input distance = output force × output distance.

and the mechanical advantage is 2. Can you use this rule to state the mechanical advantage of the pulley system in Figure 8.12c?*

The mechanical advantage of the simple system in Figure 8.12c is 2. Notice that although three strands of rope are shown, only two strands actually support the load. The upper pulley serves only to change the direction of the force. Actually experimenting with a variety of pulley systems is much more beneficial than reading about them in a textbook, so try to get your hands on some pulleys, in or out of class. They're fun.

The pulley system shown in Figure 8.13 is a bit more complex, but the principles of energy conservation are the same. When the rope is pulled 5 m with a force of 100 N, a 500-N load is lifted 1 m. The mechanical advantage is (500 N)/(100 N), or 5. Force is multiplied at the expense of distance. The mechanical advantage can also be found from the ratio of distances: (input distance)/(output distance) = 5.

No machine can put out more energy than is put into it. No machine can create energy. A machine can only transfer energy from one place to another or transform it from one form to another.

8.8 Efficiency

mportant Term

efficiency

More on efficiency in Chapter 24.

The previous examples of machines were considered to be *ideal*. All the work input was transferred to work output. An ideal machine would have 100% efficiency. In practice, 100% efficiency never happens, and we can never expect it to happen. In any machine, some energy is transformed into atomic or molecular kinetic energy—making the machine warmer. We say this wasted energy is dissipated as heat.**

When a simple lever rocks about its fulcrum, or a pulley turns about its axis, a small fraction of input energy is converted into thermal energy. We may put in 100 J of work on a lever and get out 98 J of work. The lever is then 98% efficient and we lose only 2 J of work input as heat. In a pulley system, a larger fraction of input energy is lost as heat. For example, if we do 100 J of work, the friction on the pulleys as they turn and rub on their axle can dissipate 40 J of heat energy. So the work output is only 60 J and the pulley system has an efficiency of 60%. The lower the efficiency of a machine, the greater is the amount of energy wasted as heat.

* The number-of-strands rule applies only to simple pulleys, where same-size pulleys are on the same shaft. The chain hoist popular in auto repair shops, for example, gets its mechanical advantage from different-size pulleys on the same shaft. We won't treat the chain hoist here.

** Energy of atomic or molecular motion is actually *thermal energy*, not *heat*. We'll see in Chapter 21 that heat is energy being transferred from one place to another by atomic and molecular motion. Heat is analogous to work; both involve energy transfer by motion.

Efficiency can be expressed as the ratio of useful work output to total work input.

$$\text{efficiency} = \frac{\text{useful work output}}{\text{total work input}}$$

An inclined plane is a machine. Sliding a load up an incline requires less force than lifting it vertically. Figure 8.14 shows a 5-m inclined plane with its high end elevated by 1 m. Using the plane to elevate a heavy load, we push the load five times farther than we lift it vertically. If friction is negligible, we need apply only one-fifth of the force required to lift the load vertically. The inclined plane has a *theoretical* mechanical advantage of 5.

As you push the crate, the crate pushes on molecules of the ramp (due to friction), causing them to move too. So some of your work is lost to the ramp through friction.

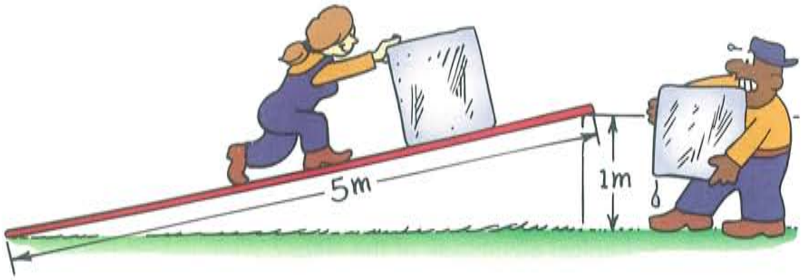


Figure 8.14
Pushing the block of ice 5 times farther up the incline than the vertical distance it's lifted requires a force of only one-fifth its weight. Whether pushed up the plane or simply lifted, the ice gains the same amount of PE.

A block of ice sliding along an icy plank, or a horse-pulled cart with well-lubricated wheels, might have an efficiency of almost 100%. However, when the load is a wooden crate sliding on a wooden plank, both the actual mechanical advantage and the efficiency will be considerably less. Efficiency can also be expressed as the ratio of actual mechanical advantage to theoretical mechanical advantage.

$$\text{efficiency} = \frac{\text{actual mechanical advantage}}{\text{theoretical mechanical advantage}}$$

Efficiency will always be a fraction less than 1. To convert efficiency to percent, we simply express it as a decimal and multiply by 100%. For example, an efficiency of 0.25 expressed in percent is $0.25 \times 100\%$, or 25%.

The auto jack shown in Figure 8.15 is actually an inclined plane wrapped around a cylinder. You can see that a single turn of the handle raises the load a relatively small distance. If the circular distance the handle is moved is 500 times greater than the pitch, which is the distance between ridges, then the theoretical mechanical advantage of the jack is 500.* No wonder a child can raise a loaded moving van with one of these devices! In practice there is a great deal of friction

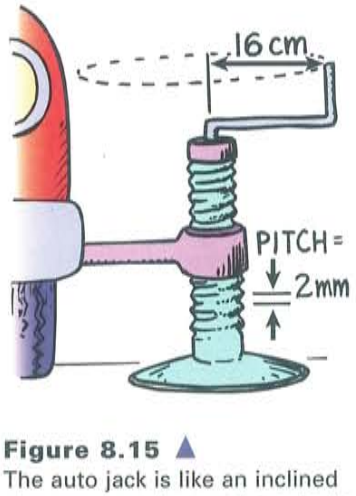


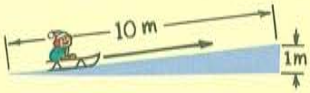
Figure 8.15
The auto jack is like an inclined plane wrapped around a cylinder. Every time the handle is turned one revolution, the load is raised a distance of one pitch.

* To raise a load by 2 mm the handle has to be turned once, through a distance equal to the circumference of the circular path of the 16-cm radius. This distance is 100 cm (since the circumference is $2\pi r = 2 \times 3.14 \times 16\text{ cm} = 100\text{ cm}$). A simple calculation will show that the 100-cm work-input distance is 500 times greater than the work-output distance of 2 mm. If the jack were 100% efficient, then the input force would be multiplied by 500 times. The theoretical mechanical advantage of the jack is 500.

in this type of jack, so the efficiency might be about 20%. Thus the jack actually multiplies force by about 100 times, so the actual mechanical advantage approximates an impressive 100. Imagine the value of one of these devices if it had been available when the great pyramids were being built!

Question

A child on a sled (total weight 500 N) is pulled up a 10-m slope that elevates her a vertical distance of 1 m.



a. What is the theoretical mechanical advantage of the slope?

b. If the slope is without friction, and she is pulled up the slope at constant speed, what will be the tension in the rope?

c. Considering the practical case where friction *is* present, suppose the tension in the rope were actually 100 N. What is the actual mechanical advantage of the slope? What would the efficiency be?

An automobile engine is a machine that transforms chemical energy stored in fuel into mechanical energy. The molecules of the gasoline break up as the fuel burns. Burning is a chemical reaction in which atoms combine with the oxygen in the air. Carbon atoms from the gasoline combine with oxygen atoms to form carbon dioxide, hydrogen atoms combine with oxygen, and energy is released. The converted energy is used to run the engine.

It would be nice if all this energy were converted to mechanical energy, but as physicists learned in the nineteenth century, transforming 100% of thermal energy into mechanical energy is not possible. Some heat must flow from the engine. Friction adds more to the energy loss. Even the best-designed engines are unlikely to be more

Answer

a. The ideal, or theoretical, mechanical advantage is

$$\frac{\text{input distance}}{\text{output distance}} = \frac{10\ \text{m}}{1\ \text{m}} = 10$$

b. 50 N. With no friction, ideal mechanical advantage and actual mechanical advantage would be the same, 10. So the rope tension, or the input force, will be 1/10 the weight being raised, 500 N. (Note that this input force is the same as the component of the child's weight along the slope.)

c. The actual mechanical advantage is (weight being raised)/(input force) = (500 N)/(100 N) = 5. The efficiency would then be 0.5 or 50%, since (actual mechanical advantage)/(theoretical mechanical advantage) = 5/10 = 0.5. The efficiency can also be obtained from the ratio (useful work output)/(work input).

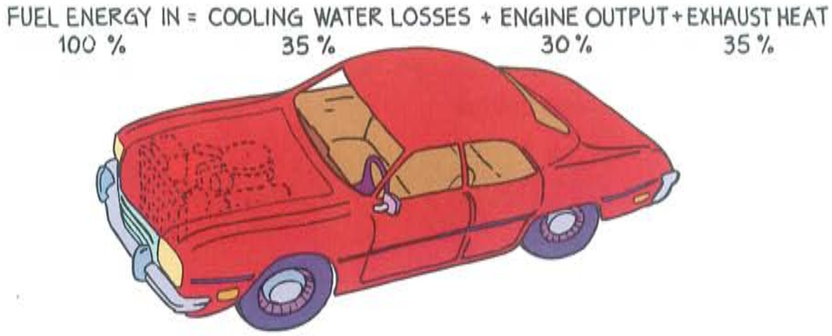


Figure 8.16
Only 30% of the energy produced by burning gasoline in a typical automobile engine becomes useful mechanical energy.

than 35% efficient. Some of the heat energy goes into the cooling system and is released through the radiator to the air. Some of it goes out the tailpipe with the exhaust gases, and almost half goes into heating engine parts as a result of friction. On top of these contributors to inefficiency, the fuel does not burn completely. A certain amount of it goes unused. We can look at inefficiency in this way: In any transformation there is a dilution of the amount of *useful energy.* Useful energy ultimately becomes thermal energy. Energy is not destroyed, it is simply degraded. Through heat transfer, thermal energy is the graveyard of useful energy.

This is much like one of your students sharing his or her lunch (energy) with 100 other students. Rather than one student with a lot of energy, now there are many students, each with a little energy. It has been diluted.

8.9 Energy for Life

Every living cell in every organism is a machine. Like any machine, living cells need an energy supply. Most living organisms on this planet feed on various hydrocarbon compounds that release energy when they react with oxygen. Just as there is more energy stored in gasoline than in the products of its combustion, there is more energy stored in the molecules in food than there is in the reaction products after the food is digested. The energy difference is what sustains life.

The same principle of combustion occurs in the digestion of food in the body and the burning of fossil fuels in mechanical engines. The main difference is the rate at which the reactions take place. During digestion, the reaction rate is much slower and energy is released as it is needed by the body. Like the burning of fossil fuels, the reaction is self-sustaining once it starts. In digestion, carbon combines with oxygen to form carbon dioxide.

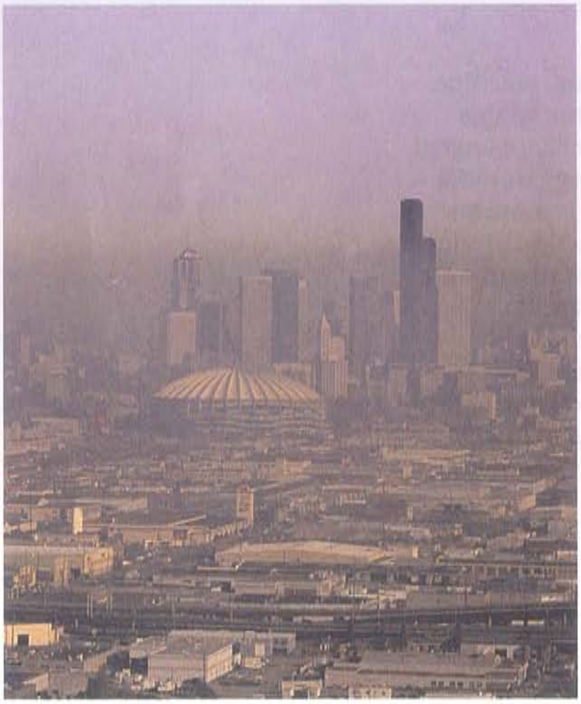
The reverse process is more difficult. Only green plants and certain one-celled organisms can make carbon dioxide combine with water to produce hydrocarbon compounds such as sugar. This process is *photosynthesis* and requires an energy input, which normally comes from sunlight. Sugar is the simplest food. All other foods, such as carbohydrates, proteins, and fats, are also synthesized compounds containing carbon, hydrogen, oxygen, and other elements. Aren't we very fortunate that green plants are able to use the energy of sunlight to make food that gives us and all other organisms energy? Because of this, there is life.

Science, Technology, and Society

Energy Conservation

Most energy consumed in America comes from fossil fuels. Oil, natural gas, and coal supply the energy for almost all our industry and technology. Nearly 70% of electrical power in the United States comes from fossil fuels, with only 21% from nuclear power. Worldwide, fossil fuels also account for most energy consumption. We have grown to depend on fossil fuels because they have been plentiful and inexpensive. Until recently, our consumption was small enough that we could ignore their environmental impact.

But things have changed. Fossil fuels are being consumed at a rate that threatens to deplete the entire world supply. Locally and globally, our fossil fuel consumption is measurably polluting the air we breathe and the water we drink. Yet, despite these problems, many people consider fossil fuels to be as inexhaustible as the sun's glow and as acceptable as Mom's apple pie, because these fuels have lasted and nurtured us through the twentieth century. Financially, fossil fuels are still a bargain, but this is destined to change. Environmentally, the costs are already dramatic. Some other fuel must take the place of fossil fuels if we are to maintain the industry and technology to which we are accustomed. The French have chosen nuclear, with 74% of their electricity coming from nuclear power plants. What energy source would you choose as an alternative?



In the meantime, we shouldn't waste energy. As individuals, we should limit the consumption of useful energy by such measures as turning off unused electric appliances, using less hot water, going easy on heating and air conditioning, and driving energy-efficient automobiles. By doing these things, we are conserving *useful* energy. In how many reasonable ways can we limit energy consumption?

8 Chapter Review

For fuller explanations, see the TE notes in the front of this book.

Concept Summary

When a constant force moves an object in the direction of the force, the work done equals the product of the force and the distance the object is moved.

- Power is the rate at which work is done.

The energy of an object enables it to do work.

- Mechanical energy is due to the position of something (potential energy) or the movement of something (kinetic energy).

The law of conservation of energy states that energy cannot be created or destroyed.

- Energy can be transformed from one form into another.

A machine is a device for multiplying force or changing the direction of force.

- The lever, pulley, and inclined plane are simple machines.
- The useful work output of a machine is less than the total work input.

Important Terms

efficiency (8.8)	machine (8.7)
energy (8.3)	mechanical advantage (8.7)
fulcrum (8.7)	mechanical energy (8.3)
joule (8.1)	potential energy (8.4)
kinetic energy (8.5)	power (8.2)
law of conservation of energy (8.6)	pulley (8.7)
	watt (8.2)
lever (8.7)	work (8.1)

Review Questions

Recall of key chapter ideas

1. A force sets an object in motion. When the force is multiplied by the time of its application, we call the quantity *impulse*, which changes the *momentum* of that object. What do we call the quantity *force* × *distance*, and what quantity can this change? (8.1) Work; changes object's energy
2. Work is required to lift a barbell. How many times more work is required to lift the barbell three times as high? (8.1) Three times the work
3. Which requires more work, lifting a 10-kg load a vertical distance of 2 m or lifting a 5-kg load a vertical distance of 4 m? (8.1) Both the same, 200 J
4. How many joules of work are done on an object when a force of 10 N pushes it a distance of 10 m? (8.1) 10 N × 10 m = 100 J
5. How much power is required to do 100 J of work on an object in a time of 0.5 s? How much power is required if the same work is done in 1 s? (8.2) 100 J/0.5 s = 200 W; 100 J/1 s = 100 W
6. What are the two main forms of mechanical energy? (8.3) PE and KE
7. **a.** If you do 100 J of work to elevate a bucket of water, what is its gravitational potential energy relative to its starting position? 100 J

   b. What would the gravitational potential energy be if the bucket were raised twice as high? (8.4) 200 J
8. A boulder is raised above the ground so that its potential energy relative to the ground is 200 J. Then it is dropped. What is its kinetic energy just before it hits the ground? (8.5) 200 J
9. Suppose an automobile has 2000 J of kinetic energy. When it moves at twice the speed, what will be its kinetic energy? What's its kinetic energy at three times the speed? (8.5) 8000 J; 18 000 J
10. What will be the *kinetic* energy of an arrow having a *potential* energy of 50 J after it is shot from a bow? (8.6) 50 J
11. What does it mean to say that in any system the total energy score stays the same? (8.6) Energy is conserved.
12. In what sense is energy from coal actually solar energy? (8.6) Material of coal was produced by sun's energy.

13. How does the amount of work done on an automobile by its engine relate to the energy content of the gasoline? (8.6) Work by engine is less than energy in tank.

14. In what two ways can a machine alter an input force? (8.7) Can change its magnitude and/or direction

15. In what way is a machine subject to the law of energy conservation? Is it possible for a machine to multiply energy or work input? (8.7) Work out cannot exceed work in; no

16. What does it mean to say that a machine has a certain mechanical advantage? (8.7) Can multiply force by a certain amount

17. In which type of lever is the output force smaller than the input force? (8.7) Type 3—always, Type 1—maybe

18. What is the efficiency of a machine that requires 100 J of input energy to do 35 J of useful work? (8.8) 35%

19. Distinguish between theoretical mechanical advantage and actual mechanical advantage. How would these compare if a machine were 100% efficient? (8.8) TMA—no friction, AMA—with friction; same

20. What is the efficiency of her body when a cyclist expends 1000 W of power to deliver mechanical energy to the bicycle at the rate of 100 W? (8.8) 10%

Plug and Chug

Math reinforcement—conceptual development through applied problem solving

1. Calculate the work done when a 20-N force pushes a cart 3.5 m. $W = Fd = 20\text{ N} \times 3.5\text{ m} = 70\text{ J}$

2. Calculate the work done in lifting a 500-N barbell 2.2 m above the floor. What is the potential energy of the barbell when it is lifted to this height? $W = Fd = 500\text{ N} \times 2.2\text{ m} = 1100\text{ J}$; PE = 1100 J

3. Calculate the power expended when the barbell above is lifted 2.2 m in 2 s. $P = W/t = 1100\text{ J}/2\text{ s} = 550\text{ W}$

4. **a.** Calculate the work needed to lift a 90-N block of ice a vertical distance of 3 m. What PE does it have? $W = 90\text{ N} \times 3\text{ m} = 270\text{ J}$; PE = 270 J

   b. When the same block of ice is raised the same vertical distance by pushing it up a 5-m long inclined plane, only 54 N of force are required. Calculate the work done to push the block up the plane. What PE does it have? $W = 54\text{ N} \times 5 = 270\text{ J}$; same

5. Calculate the change in potential energy of 8 million kg of water dropping 50 m over Niagara Falls. $\Delta PE = mg\Delta h = 8\,000\,000\text{ kg} \times 10\text{ m/s}^2 \times 50\text{ m} = 4000\text{ MJ}$

6. If 8 million kg of water flows over Niagara Falls each second, calculate the power available at the bottom of the falls. $P = E/t = 4000\text{ MJ}/1\text{ s} = 4000\text{ MW}$

7. **a.** Calculate the kinetic energy of a 3-kg toy cart that moves at 4 m/s. $KE = (1/2)mv^2 = (0.5)(3\text{ kg})(4\text{ m/s})^2 = 24\text{ J}$

   b. Calculate the kinetic energy of the same cart at twice the speed. $KE = 4 \times 24\text{ J} = 96\text{ J}$

8. A lever is used to lift a heavy load. When a 50-N force pushes one end of the lever down 1.2 m, the load rises 0.2 m. Calculate the weight of the load. From $(Fd)_{in} = (Fd)_{out}$, $F_{out} = (1.2\text{ m})(50\text{ N})/0.2\text{ m} = 300\text{ N}$

9. **a.** In raising a 5000-N piano with a pulley system, the workers note that for every 2 m of rope pulled down, the piano rises 0.4 m. Ideally, how much force is required to lift the piano? $F_{in} = (d_{out} \times F_{out})/d_{in} = (0.4\text{ m} \times 5000\text{ N})/2\text{ m} = 1000\text{ N}$

   b. If the workers actually pull with 2500 N of force to lift the piano, what is the efficiency of the pulley system? ideal/actual = 1000/2500 = 40%

10. Your European friends tell you they are pleased because their new car gives them 15 kilometers per liter of fuel. Translate this into miles per gallon so you can decide whether to be impressed. One mile is 1.6 km, and one gallon is 3.8 liters. $15\text{ km}/1\text{ L} \times 1\text{ mi}/1.6\text{ km} \times 3.8\text{ L}/1\text{ gal} = 35.6\text{ mi/gal}$

Think and Explain

Conceptual development through applied critical thinking

1. State two reasons why a rock projected with a slingshot will go faster if the rubber is stretched an extra distance. More stretch F + more distance = more PE; more KE

2. Does an object with momentum always have energy? Does an object with energy always have momentum? Explain. Yes; no, it may have only PE

3. If a mouse and an elephant both run with the same kinetic energy, can you say which is running faster? Explain in terms of the equation for KE. Mouse, less m, more v for same $(1/2)mv^2$

4. An astronaut in full space gear climbs a vertical ladder on the earth. Later, the astronaut makes the same climb on the moon. In which location does the gravitational potential energy of the astronaut change more? Explain. More on earth, g larger, so mgh larger

5. Most earth satellites follow an oval-shaped (elliptical) path rather than a circular path around the earth. The PE increases when the satellite moves farther from the earth. According to the law of energy conservation, does a satellite have its greatest speed when it is closest to or farthest from the earth? Greatest KE closest to earth when PE smallest

6. Why does a small, lightweight car generally have better fuel economy than a big, heavy car? How does a streamlined design improve fuel economy? Small m, less KE for given v; reduces drag

7. Does using an automobile's air conditioner while driving increase fuel consumption? What about driving with the lights on? What about playing the car radio when parked with the engine off? Explain in terms of the conservation of energy. Yes; yes; yes; because of later battery charge

8. What is the theoretical mechanical advantage for each of the three lever systems shown? One; two; one-half

9. You tell your friend that no machine can possibly put out more energy than is put into it, and your friend states that a nuclear reactor puts out more energy than is put into it. What do you say? Sorry, reactor energy is PE in uranium fuel.

10. The energy we require to live comes from the chemically stored potential energy in food, which is transformed into other energy forms during the digestion process. What happens to a person whose combined work and heat output is less than the energy consumed? What happens when the person's work and heat output is greater than the energy consumed? Can an undernourished person perform extra work without extra food? Defend your answers. Gains wt; loses wt; only at cost of own wt

Think and Solve

Math reinforcement—variable substitution and equation solving

1. A hammer falls off a rooftop and strikes the ground with a certain KE. If it fell from a roof that was four times higher, how would its KE of impact compare? Its speed of impact? (Neglect air resistance.) $4 \times$ higher, $4 \times$ PE, $4 \times$ KE; $2 \times$ speed

2. A certain car can go from 0 to 100 km/h in 10 s. If the engine delivered twice the power to the wheels, how many seconds would it take? Half the time, 5 s

3. If a car traveling at 60 km/h will skid 20 m when its brakes lock, how far will it skid if it is traveling at 120 km/h when its brakes lock? (This question is typical on some driver's license exams.) $Fd = \Delta KE$, $2 \times$ speed, $4 \times$ KE, F constant, so $d = 4 \times 20\text{ m} = 80\text{ m}$

4. How many kilometers per liter will a car go if its engine is 25% efficient and it encounters an average retarding force of 1000 N at highway speed? Assume the energy content of gasoline is 40 MJ per liter. Work/liter = 0.25(40 MJ) = 10 MJ, $d = W/F$ = 10 MJ/500 N = 20 km

5. The pulley shown on the left has a mechanical advantage of 1. What is the mechanical advantage when it is used as shown on the right? Defend your answer (1) by considering the pulley to be a lever and (2) by tension in the rope. 2; See Fig 8.12b lever; rope tension is half